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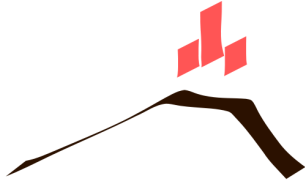
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Volcano statistics casebook: Tentative evidence from two near real-time analyses for an earth tide influence on volcano-seismic events

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Abstract

Based on rapid analyses done in near real-time and in support of scientific advice, I present two cases of *prima facie* evidence for an earth tide triggering effect on earthquake activity during two volcanic eruption episodes: the first, in relation to large magnitude earthquakes, occurred during August 2014 in the 2014 – 2015 Bárðarbunga-Holuhruan, Iceland, eruption; and the second concerns the timing of VT strings at the Soufrière Hills Volcano, Montserrat. In both cases, statistical testing of the hypothesis that the timings of the seismic events of interest and vertical earth tide phase were *not* correlated produced probabilities at or below a 5% significance level, suggesting rejection of the hypothesis can be argued. This note outlines the method used for computing earth tide amplitudes at the two volcanoes and the basis and results of the Schuster test for relative phase timings; some comments on the volcanological contexts are added. These findings suggest that further, more formal analysis may be warranted.

KEYWORDS: earth tides, volcanic earthquakes, VT strings, Schuster test, Bárðarbunga-Holuhruan, Iceland, Soufrière Hills Volcano, Montserrat

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Introduction

On various occasions over the years, I have undertaken quick statistical or semi-statistical analyses for eruption hazard and risk assessments or in support of urgent decision making by officials in crisis circumstances. The purpose of these casebook notes is to document the analysis processes followed at the time, and to provide some indications of volcanological contexts and implications. It is hoped that such case histories may encourage further statistical analysis, and prompt additional research into the observations and related phenomena. In this spirit, the present note records two instances when I made exploratory analyses of volcano-seismic data — emerging in near real-time — and found tentative evidence for an earth tide effect on event occurrence timing.

Evidence of non-randomness in the occurrences of earthquakes and volcanic eruptions due to external natural forcings has been sought for many years, but findings are mixed at best, generally inconclusive in statistical test terms, and sometimes contentious. There is an extensive literature on the subject of tides in relation to volcanic activity and eruptions, going back to *Brown (1925)* and *Espin (1909)*, and to even earlier speculations. In part, the difficulty of discerning a forcing signal or signals in a time series of volcano-seismic activity is due to the multiplicity of processes that act simultaneously with complex varying intensities over a variety of spatial scales and timescales, ranging from hours or less (tidal), to decades (climatic) and even centuries (tectonic, astronomical) (*e.g.*, *Neuberg, 2000; Jupp et al., 2004*).

This said, unequivocal evidence of tidal triggering for microearthquakes (-0.4 to 2.0 ML) on the East Pacific Rise, recorded between October 2003 and April 2004, was reported by *Stroup et al. (2007)*. Although semi-diurnal tidal stress changes at that location are small (< 2 kPa), the seismicity exhibited a significant ($> 99.9\%$) non-random temporal distribution, with events occurring preferentially near times of peak extension. Due to the proximity of this site to an ocean tidal node, where changes in sea surface height are minimal, periodic stress changes are dominated by the solid earth tide.

Stroup et al. (2007) assert that the modulation of these microearthquakes by small-amplitude periodic stresses is consistent with earthquake nucleation within an environment subjected to a high stressing rate, maintained in a critical state of near-failure by magmatic and hydrothermal processes. It would not be greatly surprising if similar circumstances existed in other volcanic systems, elsewhere.

Motivation for the earthquake-earth tide analyses

On 16 August 2014, Bárðarbunga volcano in Iceland developed a phase of strong seismic unrest, with up to thousands of earthquakes detected per day and significant deformation observed around the Bárðarbunga caldera (*Barsotti et al., 2015*). Dike intrusion was on-going for almost two weeks, followed by a small, short-lived effusive eruption on 29 August 2014, in Holuhraun. Two days later a prolonged, more intense, effusive gas-rich eruption started in that locality, which lasted until 28 February 2015.

The first days of the unrest at Bárðarbunga were notable for the significant earthquakes around the caldera — many of which exceeded magnitude 4 — and the largest of these were in turn remarkable (to me) as they appeared to exhibit a temporal pattern of repetitions, approximately every 12 hours. This emerging time series reminded me of a similar pattern of seismic events at Fernandina volcano, in the Galapagos, in 1968, when a significant caldera collapse episode took place. The seismicity of that episode was described in detail by *Filson et al. (1973)*, who noted an apparent tidal influence on seismicity timings (their Figure 19, reproduced here as Figure 1).

As the paper by *Filson et al. (1973)* is now several decades old, and may easily be overlooked, their abstract merits reproducing here (my emphasis added):

*The seismicity associated with the collapse of a volcanic caldera in the Galapagos Islands during June of 1968 has been studied in detail. The rate of seismic energy release, inferred from some 638 assigned surface wave magnitudes, was constant over a 9-day period and appears to be consistent with removal of magmatic support at a constant rate. Early in the earthquake sequence, the energy release was periodic. **Large earthquakes occurred only at 6-hour intervals coinciding with extremes in the ocean and earth tides**; however the mechanism of triggering, if any, is not clear. Alternative periodic mechanisms based on passive withdrawal or expulsion of supporting magma are suggested. Values of energy, moment, and stress drop are computed from the known source geometry and are found to compare favorably with those estimated from seismic data. Assuming a rather low rigidity, the seismic data are consistent*

with a cylindrical block of 2×10^{16} grams dropping some 300 meters in approximately 75 dislocation stages, each averaging about 4 meters. In support of this model, a cumulative frequency versus magnitude curve suggests that some 75 earthquakes larger than about M_s 4.5 were of a different genre than those smaller. Other volcanic phenomena, including eruptions and large explosions, preceded the caldera collapse and were accompanied by minor seismicity. However, major seismicity accompanied only the collapse, which apparently was the only volcanic event that included major ground deformation through shear.

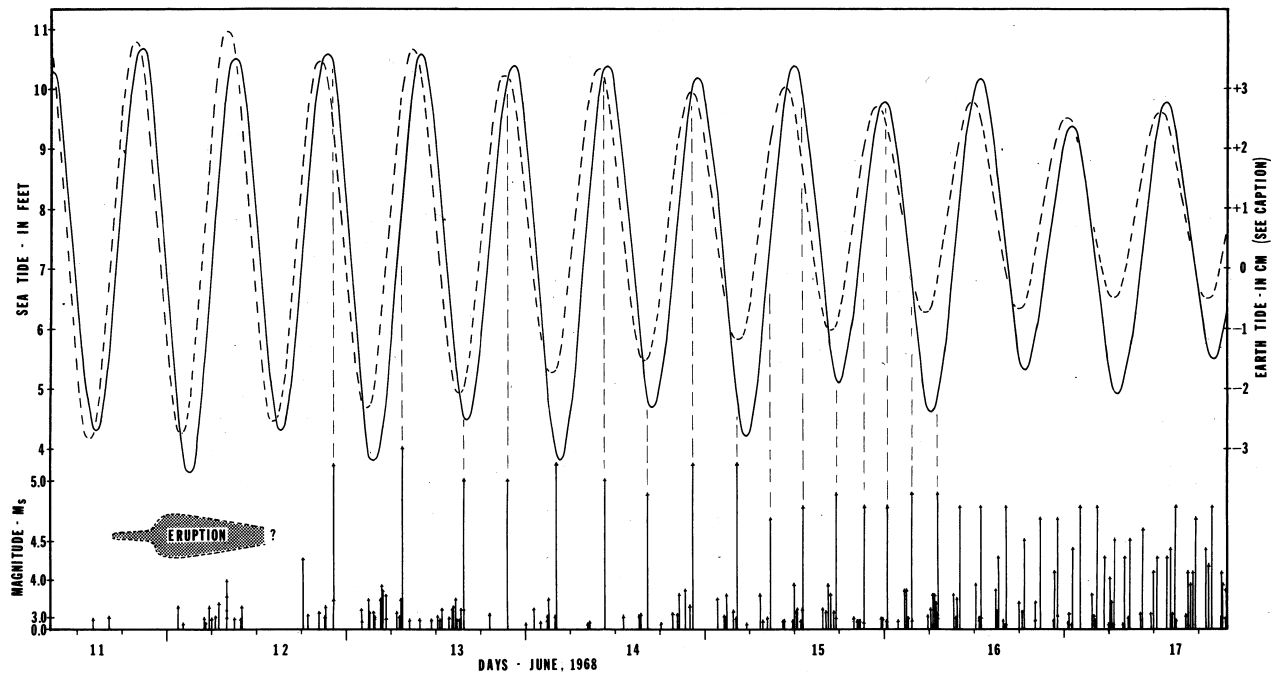


Figure 1: Fernandina caldera collapse episode, Galapagos, 1968: correlation of earthquakes (vertical bars, scaled to magnitude) with the phase of the ocean (solid line) and radial solid earth tide (dashed) during the period June 11 – 17, 1968; reproduced from Figure 19 of *Filson et al. (1973)*.

In their paper, *Filson et al. (1973)* reported that the caldera collapses, as expressed by the largest earthquakes, occurred when the volcano was under maximum horizontal tension and vertical compression due to the Earth body tide, and when the volcano was under maximum horizontal compression and vertical tension (effects due to ocean tide loading were not included in their analysis). *Filson et al. (1973)* did not, however, provide any quantitative statistical estimate of the timing correlation of these quakes with tides.

Later, *Francis (1974)* interpreted the Fernandina earthquake swarm as comprising two different types of earthquake: (1) low-stress events occurring on the main caldera fault and (2) higher stress events on minor faults. Differences in scale of these faults allowed the two types of earthquake to be distinguished by magnitude, with events occurring on the main caldera fault having a high b -value, whilst those on minor faults had a normal b -value. *Francis (1974)* inferred a small fall in magma chamber pressure leading to the collapse, and he developed a model of the volcano that could account for the magnitudes of the earthquakes observed, the stress on the main caldera fault and the seismic efficiency.

Fernandina caldera has a diameter of about 3 – 4 km, and the *Filson et al. (1973)* analysis assumed that in 1968 the whole caldera floor subsided as a unit in distinct dislocations, with the main displacements producing the large earthquakes, ranging in magnitude from M_s 4.6 – M_s 5.2. In terms of size, Fernandina caldera is thus smaller than the *ca.* 10 – 12 km diameter extent of the Bárðarbunga structure, as delineated by its mapped extent and seismicity (Figure 2).

In August 2014, the repetitive, roughly 12-hour recurrences of larger quakes in Iceland, and recollection of the Fernandina episode, prompted me to start assembling Bárðarbunga earthquake event data that were provided on-line by the Icelandic Volcano Observatory (IVO) of the Icelandic Meteorological Office (IMO). This acquisition continued until I went

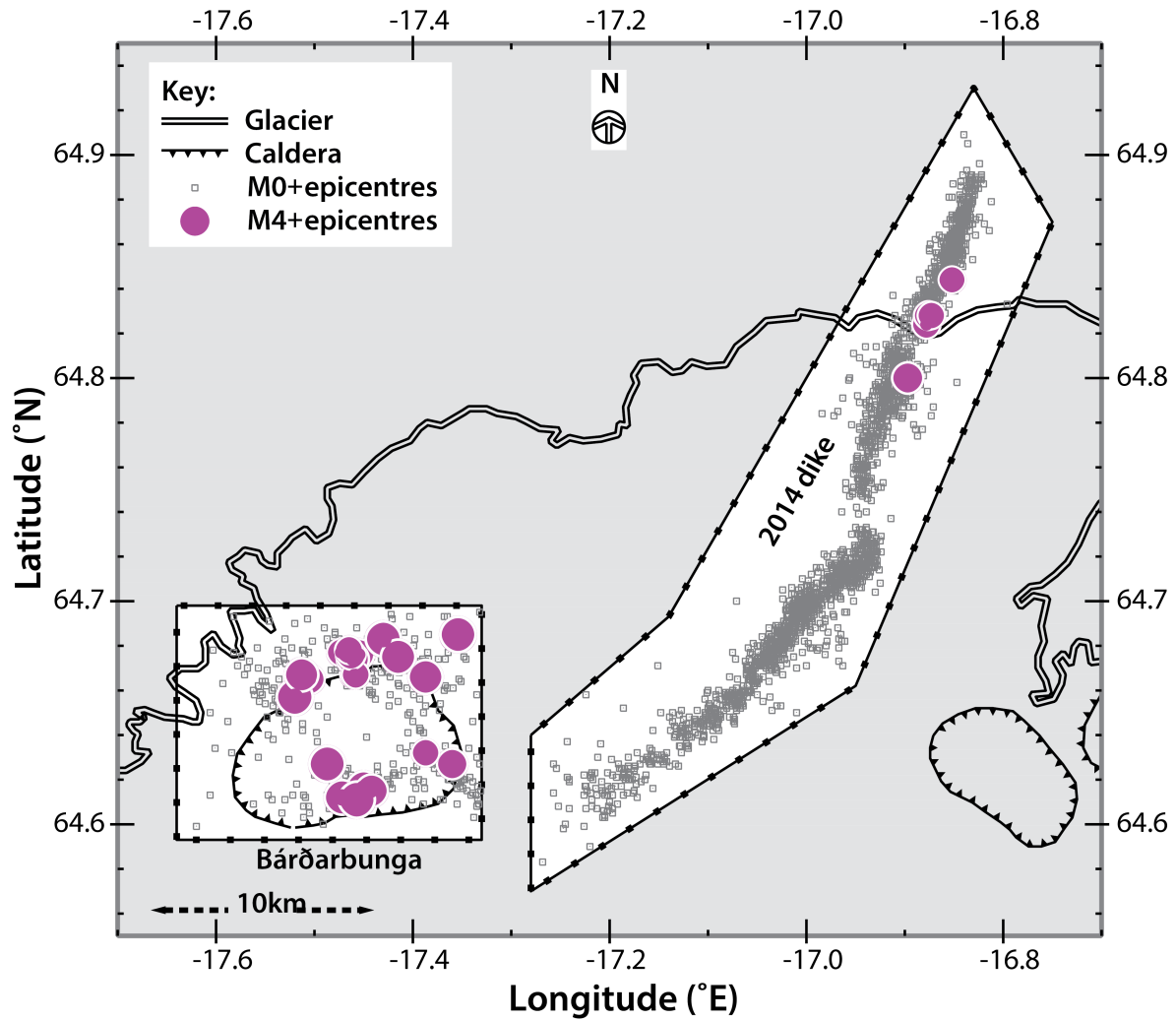


Figure 2: Map of Bárðarbunga-Holuhraun area, Iceland, showing main caldera outlines, glacier edge, earthquake epicentres in August 2014, and zones delineating seismicity associated with the caldera and with the main dike.

away on a field trip in early September 2014; subsequent event data were not retrieved.

It is against this background that I record an exploratory time series analysis done in near real-time concerning the occurrence of M4+ quakes at Bárðarbunga-Holuhraun in August 2014, and their relationship to solid earth tide stresses.

Methods

At shorter time intervals of hours to days, the time at which an earthquake occurs might depend, to some extent, on the state of tidal and other stresses in the shallow crust around the originating fault. This time dependence can be tested statistically (Woo, 2011), using a method due to Schuster (1897). For instance, the solid earth tidal stress components can be calculated at the location of the earthquake, and a phase angle estimated that expresses the relative time difference between the event and the nearest stress peak.

Following Woo (2011), for N earthquakes in a specific dataset, let the phase angle assigned to the i^{th} earthquake be ψ , and define:

$$A = \sum_{i=1}^N \left(\cos(\psi) \right) \quad \text{and} \quad B = \sum_{i=1}^N \left(\sin(\psi) \right) \quad (1)$$

The Schuster test parameter is:

$$R = \sqrt{A^2 + B^2}. \quad (2)$$

If earthquakes occur randomly with respect to tidal peaks, then A and B are distributed around zero mean with a variance of $N/2$. R^2 follows a chi-square distribution with two degrees of freedom, reminiscent of a two-dimensional random walk. This is simply the exponential distribution, so the probability that R or a larger value occurs by chance is:

$$P_R = \exp(-R^2/N). \quad (3)$$

The parameter P_R is the significance level for rejection of the null hypothesis that events occur randomly with respect to the tide phase angle (worked spreadsheet examples are provided in Supplementary Material).

The Schuster test has been adopted routinely in seismology for detecting non-random earthquake occurrences (e.g., mining induced events). It is also the fundamental basis for a new analysis by Brinkman *et al.* (2015), showing daily tide stresses correlate significantly with small earthquakes, just before large earthquakes. From real and synthetic data, Brinkman *et al.* (2015) conclude that such correlation could provide information about the likelihood of an impending large earthquake.

To determine time series of earth tide amplitudes at Bárðarbunga throughout August 2014, I used the computer program, `solid.for`, coded by Milbert (2015)¹. Milbert's code is based on an earlier Fortran code, `dehanttideinelmjd.f`, provided originally by Professor Veronique Dehant of the Royal Observatory of Belgium.²

In the two cases discussed here, Bárðarbunga-Holuhraun during the year 2014 and the period during 2013–2014 at Soufrière Hills, Montserrat, analyses were restricted to testing earthquake occurrence timings against changes in the amplitude of the vertical component of the solid earth tide; smaller horizontal earth tide component(s), and oceanic and atmospheric tides were not considered.

Bárðarbunga-Holuhraun eruption 2014

Figure 3a shows vertical earth tide amplitude in metres at Bárðarbunga for the period of 01 August 2014 to 02 September 2014, calculated with the program `solid.for`, together with all earthquakes with magnitude greater than $M=0$, and caldera and dike quakes with $M=2.5$ or greater (see Figure 2 for the spatial definition of the caldera and diking zones).

The plot of time-of-occurrence of M4+ quakes against vertical earth tide displacement (Figure 3b) reveals an apparent association with tide reversals, specifically, and applying the Schuster test to the 27 events in Figure 3b produces $R^2 = 90$ and $P_R = 0.05$ (refer to Excel workbook calculations in Supplementary Material). In other words, the result is marginally statistically significant for rejecting the hypothesis of random timings ($p = 0.05$ is the rejection criterion).

¹A MatLab implementation of Milbert's code is available from:

<http://www.mathworks.com/examples/matlab/community/13117-earthtide-documentation> (accessed 24 March 2016).

²The solid earth tide computational algorithm is documented in section 7.1.2 of McCarthy & Petit (2004).

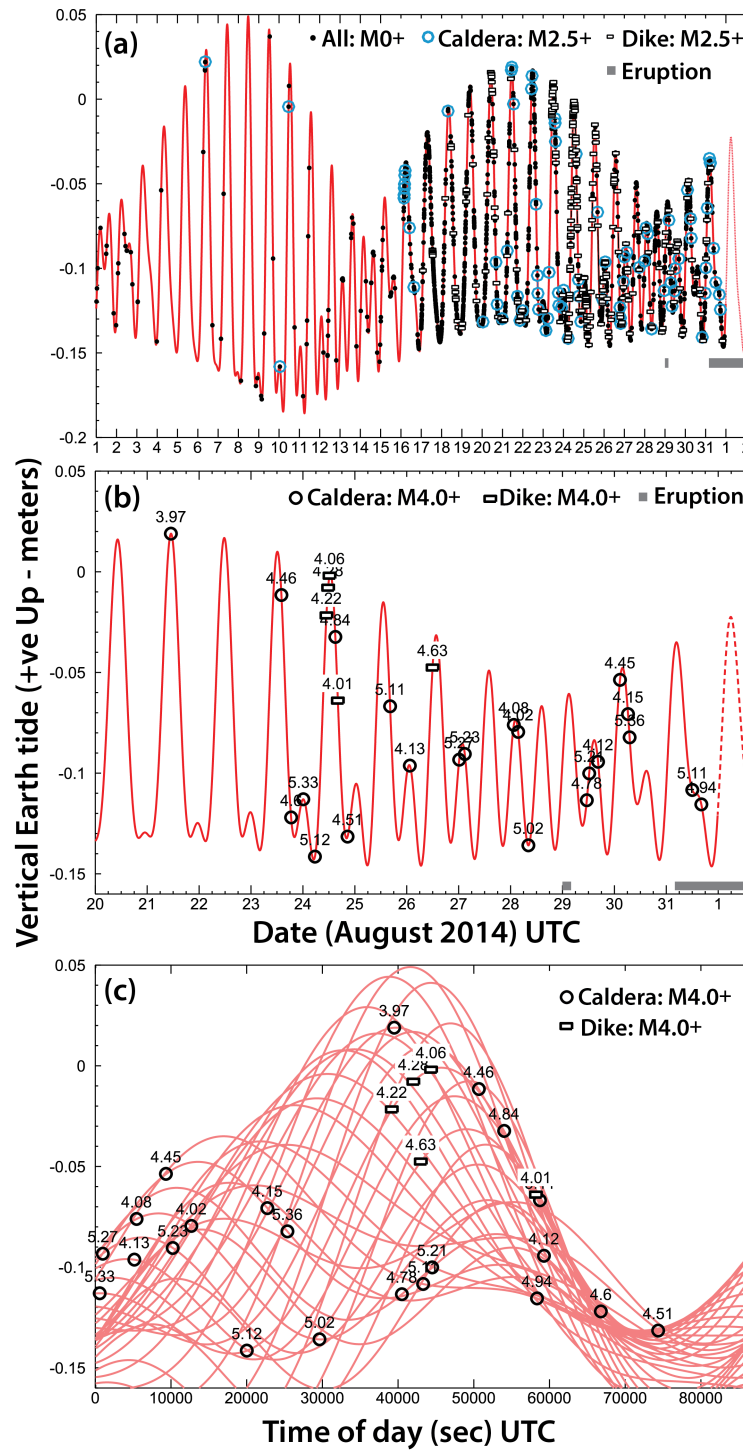


Figure 3: Vertical Earth tide amplitude at Bárðarbunga and times of earthquakes: (a) all events, 1 – 31 August 2014; (b) M4+ events by zone, 20 – 31 August 2014; (c) earthquakes and tides against time-of-day (see text). Times are UTC (= local time). (IMO reviewed hypocentre data)

Four of these earthquakes are timed close to tidal minima, rather than maxima. If these are excluded, the Schuster P_R value reduces to 0.001, *i.e.*, a very low probability of arising by chance. Thus, it seems likely that all 27 candidate M4+ quakes are strongly linked to vertical earth tide *reversals*. This specific proposition was not tested at the time, but would be amenable to formal analysis. And, of course, the analysis could be extended to events occurring after the end of August 2014, to see whether correlation was sustained, or broke down eventually; if the latter was found to be the case, this could indicate some critical change in system conditions.

An alternative hypothesis might be that transient events with characteristic repeat intervals of about 12 hours could be reflecting some diurnal or semi-diurnal forcing pattern; with a short time series of a few days duration, it is very difficult to tell whether there is a diurnal or semidiurnal variation (24 hr or 12 hr) as opposed to a tidal forcing effect (24:50 hr and 12:25 hr)³. Figure 3c shows the Bárðarbunga M4+ earthquake data plotted versus time of day. Whilst the series is too short for the tidal peaks to have swept out the full 24 hour span, the earthquakes are spread fairly uniformly throughout the hours of the day, and thus evince little obvious sign of a systematic diurnal or semi-diurnal variation. It should be feasible to check this inference more formally using the much more extensive data from the whole Bárðarbunga eruption episode.

Discussion of the Bárðarbunga case

The observation of an apparent tidal linkage in the first few days of the Bárðarbunga episode, and similarities with the 1968 Fernandina, Galapagos case, prompted conjecture about the causal mechanism of these earthquakes, and their relation to subsequent magma production in the dike and eruption episode. This was pertinent because, in contemplating early stage advice for the UK authorities (anxious about a repeat of the disruptive effects of the 2010 Eyjafjallajökull, Iceland, eruption), a number of potential future scenarios needed to be considered, with the possible duration of eruption one of the most important aspects of concern.

A favoured explanation for caldera formation is magma body under-pressure or withdrawal of magma, reducing support under the so-called roof rock. This concept has been adopted to explain geophysical observations (*e.g.*, [Peltier et al., 2008](#); [Kusumoto & Gudmundsson, 2009](#)) and as a basis for analogue models ([Acocella et al., 2000](#); [Holohan et al., 2011](#)), and latterly has been invoked to explain ice surface subsidence at Bárðarbunga in 2014 – 2015 ([Sigmundsson et al., 2015](#)). A variant hypothesis, pertinent to the Bárðarbunga case, is that lavas in large fissure eruptions can be fed by regional-scale vertical channelling dikes, injecting magma into shallow sills from much deeper reservoirs ([Gudmundsson et al., 2014](#)). [Browning & Gudmundsson \(2015\)](#) adopted this argument in their modelling of the Bárðarbunga episode, suggesting that the ring-fault subsidence in the caldera was triggered by modest upward doming of the volcanic system due to magma injection and pressurization.

However, given the fact that significant normal faulting seismicity in early August 2014 preceded seismicity associated with eventual dike growth towards Houhraun, and given also that the timings of the biggest quakes seemed linked to tidal conditions, for exhaustiveness in a hazard assessment, I considered an alternative hypothetical model. My line of argument, rightly or wrongly, was as follows: continuing long-term plate-scale extensional movement across Iceland could have led to a localized reduction of normal stress, engendering rifting of the crust and some upward migration of magma. In the case of the caldera, these fault dislocations became incipient with time, and so their timings were *triggered*, but not directly caused, by superimposed tidal stresses. In this conceptual model, the resulting instantaneous block drops increased pressure in a pre-existing shallow magma body and eventually helped piston magma into the dike, the latter structure also primed towards opening by the on-going tectonic extension. If the predominant or sole stressor mechanism in the volcano had been magma self-pressurization and/or vertical injection, then, I reasoned, the caldera floor would have been experiencing sustained upward support in early August 2014, and normal faulting would have been opposed.

Moving this model forward in semi-quantitative form, during August 2014 there had been about 22 caldera quakes with magnitudes of M4 or greater (Figure 3), that is, about one-third of the corresponding number of big events at Fernandina. Assuming the Bárðarbunga activity could be represented by a single, subsiding block of similar dimension to that invoked in the [Filson et al. \(1973\)](#) Fernandina model, then a simple scaling of 22 events would produce a total of approximately 100 m of subsidence, spread over an area that is $\sim 15\times$ greater, in other words, about 7 m of subsidence overall, if the whole Bárðarbunga caldera floor was dropping down as a unitary block. This simplistic scenario was adopted as a first order model; the spatial distribution of the big event epicentres suggests most of the footprint area of the caldera was bounded

³I am grateful to the reviewer for raising this point.

by active seismicity at the time (Figure 2). Also it is conceivable that such a net amount of distributed subsidence would not have been easily and punctually detected visually, because of masking by the covering Vatnajökull glacier.

Taking the analogy with Fernandina a step further, this amount of subsidence, if effected across the whole crater floor area, equates to an overall sub-surface volume reduction of about $700 \times 10^6 \text{ m}^3$, *i.e.*, not grossly incommensurate with the reported volume of magma intruded into the dike by 06 September 2014, which was put at about $\sim 500 \times 10^6 \text{ m}^3$. Of course, these were quick, and very tentative estimates; more recently, *Riel et al. (2015)* and *Browning & Gudmundsson (2015)*, among others, have considered the collapse parameters of the Bárðarbunga caldera in much greater detail.

In terms of its immediate consideration, one implication of this roof block pistoning model, if it had any validity in reality, was that magma intrusion, and then eruption, would continue for as long as the conditions persisted in which magma was available at shallow depth for expulsion into the dike. Thus, it seemed plausible that the eruptive episode would continue until the available magma volume was critically reduced, or until the volcano structure and its faults evolved to a changed, metastable sub-critical stress state with further downward block movements being impeded, *e.g.*, due to increased effective normal stresses.

In principle, changes that would inhibit further fault dislocations might have been detected, say, by monitoring earthquake stress drops or stress tensor orientations; therefore I gave my support to advisory recommendations for enhanced instrumental monitoring at Bárðarbunga.

As a postscript on the subject of anticipated eruption duration, on 11 October 2014, six weeks after the eruption started, it is reported that Professor Haraldur Sigurðsson made a prediction that the eruption would come to an end in March 2015 (*Icelandic News, 2015*). His forecast was based on observation of an early exponential decay in the subsidence of the centre of the Bárðarbunga caldera (*Sigurðsson, 2015*), with the interpretation that the pressure in the volcanic system that supplied magma to the Holuhraun eruption was gradually being relieved. In due course, the eruption ended, almost exactly when Sigurðsson had predicted!

It can be argued that the kinematic efficiency of magma expulsion by roof block pistoning, as outlined above, might also reduce with a quasi-exponential decay as volumetric constriction progressively resisted the dropping movement of the crater floor and as increasing normal stresses tightened their grip. The caldera pistoning model, prompted by the repeating large earthquakes, was one alternative conceptual driver for eruption that I pondered as events unfolded at Bárðarbunga caldera and at Holuhraun; however, more detailed, critical appraisal may show it is not a viable explanation of the volcanological processes that took place, and others may care to critique this notion.

Soufrière Hills Volcano VT–strings 2013 – 2014

The eruption of the Soufrière Hills Volcano (SHV), Montserrat, started in July 1995 (*Druitt & Kokelaar, 2002*) and surface activity continued in phases with intervening pauses until February 2010 (*Wadge et al., 2014*).

Since late 2007, and following the third major phase of SHV eruptive activity (*Wadge et al., 2014*), short-lived, intense swarms of volcano-tectonic (VT) earthquakes with distinctive temporal patterns started occurring at the volcano (see, *e.g.*, *Stewart et al., 2014*; *Smith, 2014*); notably, these swarms had not been seen in the preceding twelve years of activity. These strings, usually referred to at SHV as VT strings (elsewhere, sometimes called *spasmodic bursts*) are closely related in time (typically, all within a 1 hour period), and in a restricted hypocentral volume, in the case of SHV at a depth of 3 – 5 km below the volcano. However, unlike some other swarms or clusters of repeating VT events at this volcano (and elsewhere), the member events of a VT string do not exhibit a common pattern of similar waveforms or source mechanisms, each is a distinct, unique event in its own right. An explanation for their cause, or causes, remains elusive.

As anything that throws light on the properties of VT strings may be informative, and having just discerned possible evidence for a tidal influence on seismic events at Bárðarbunga, I undertook an exploratory analysis of a sample of VT strings at SHV that had been detected between March 2013 and July 2014 (at the time of writing, a complete catalogue of SHV strings is being compiled by the Montserrat Volcano Observatory MVO (*Smith, 2016, personal communication*)).

Program `solid.for` was again used to compute a time series of the vertical earth tide amplitudes at this volcano on the eight dates of interest, and tidal displacements for each day are shown on Figure 4, together with the timings of ten VT strings.

Using the first event of each string as the reference time for VT string phasing relative to the tidal maximum, Schuster's test on these ten data points produces a $P_R = 0.04$ (see Supplementary Material). As a reminder, the parameter P_R is the significance level for rejection of the null hypothesis that events occur randomly with respect to the tide phase angle.

As was the case with Bárðarbunga, some of these VT strings occur at tidal minima, and hence are more likely associated

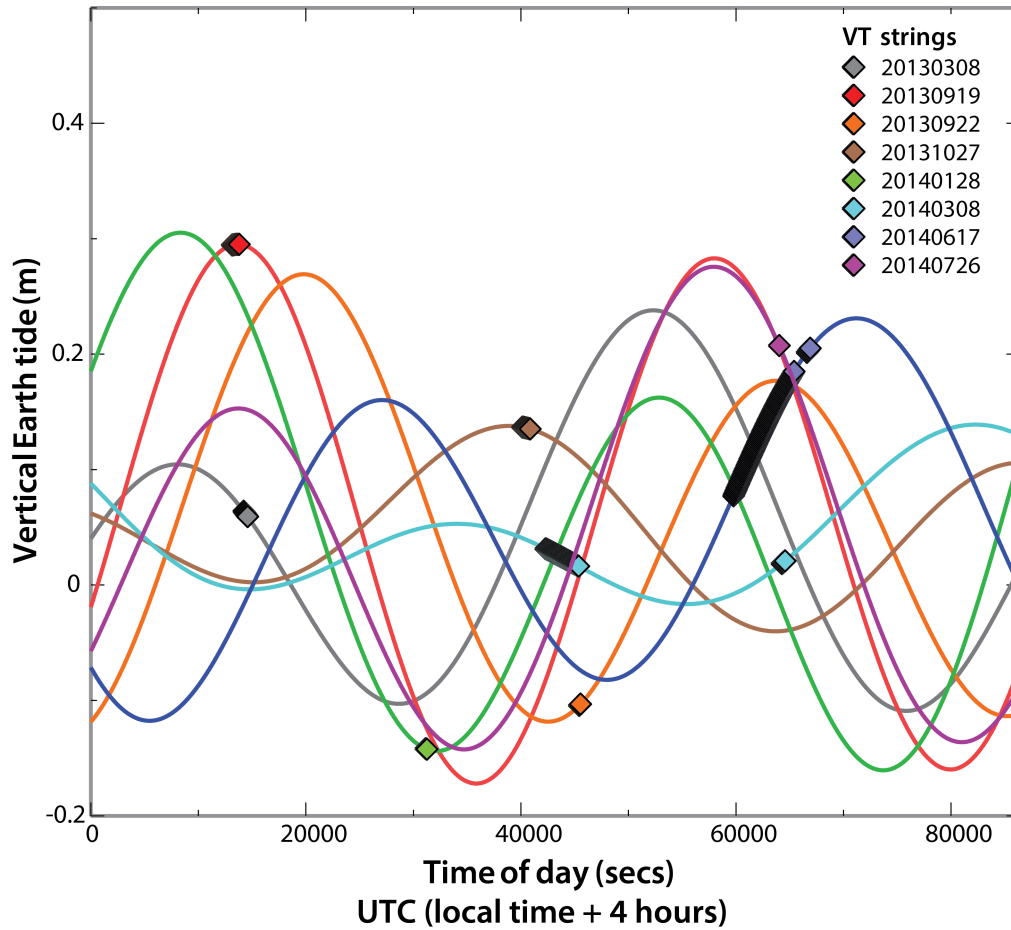


Figure 4: Computed diurnal vertical earth tide amplitudes at Soufrière Hills Volcano, Montserrat, on days with VT strings during March 2013 to July 2014. Timings are expressed as seconds in the 24-hour day (UTC). VT string data courtesy of the Montserrat Volcano Observatory (MVO).

with stress reversals, rather than moments of maximal displacement. While the SHV VT string dataset is sparser than the dataset from Bárðarbunga for examining temporal properties, there is no hint in Figure 4 of any systematic diurnal or semi-diurnal variation in the timings of these VT strings.

At SHV, some VT strings have occurred simultaneously with elevated SO₂ emission rates and it has been conjectured that these events may be associated with gas release from depth through brittle fracturing and opening of cracks within the volcanic edifice (*Christopher et al.*, 2015). However, strings have occurred there that were not followed by subsequent degassing, tremor signals or other observable activity or changes at the surface (*Stewart et al.*, 2014).

Thus, although there appears to be some, not insubstantial, evidence for a relationship with degassing, the exact cause of the events that comprise a VT string is still uncertain, and the circumstances that are conducive to VTs occurring in strings remain enigmatic.

Conclusions

Volcanology’s accumulated records of monitoring and observations contain several instances of short-lived and transient episodes when eruptive activity or seismic events appeared to respond to tidal forcing. One good example occurred about two months prior to the 18 May 1980 Mt. St. Helens eruption, when a weak but significant correlation was present between two classes of earthquakes and tides for a time interval of about 10 days (*McNutt & Beavan*, 1984). In this instance, *McNutt & Beavan* (1984) calculated solid Earth stress and strain tides at a hypocentral depth of 4 km, and also calculated stress and strain tides induced by ocean loading (the latter amplitudes were typically 20 – 40% of the solid earth tide amplitudes at the location of Mt. St. Helens). In each case, the phase of the correlation changed systematically with time, but there were no significant correlations between tides and the number of events or energy release of the identified two classes of earthquakes during any other interval between the 20th of March and 18th of May 1980. The other two classes of events in their taxonomy showed no evidence of significant tidal correlation at any time during the study period.

The 1980 Mt. St. Helens case illustrates the ephemeral and enigmatic nature of tidal influences on volcanic activity. Here I present new *prima facie* evidence for a potentially significant tidal triggering effect on earthquake activity during August 2014 during the 2014 – 2015 Bárðarbunga- Holuhruan, Iceland, eruption, and for a similar relationship for the onset timing of VT strings at the Soufrière Hills Volcano, Montserrat, during later years of that eruption. Further work is warranted to refine the tide-quake timing correlation analysis of these, and other episodes, and to explore in more detail the spatio-temporal evolution of seismicity, stresses and strains, and their properties and relationships to the structural and geometrical properties of the volcanoes, stress fields and diking. The development of a novel, small, low-cost gravimeter technology *Middlemiss et al.* (2016) opens up exciting new prospects for detailed field measurements of gravity, and tidal effects, at volcanoes.

Disentangling the complexities involved in tidal processes (see, *e.g.*, *Neuberg*, 2000) calls for more detailed and comprehensive analysis techniques that I was able to deploy in short order for hazard assessment purposes. For example, the program `solid.for` does not implement ocean loading, atmospheric loading, or deformation due to polar motion; GOTIC2 (*Matsumoto et al.*, 2001) and Tsoft (*Van Camp & Vauterin*, 2005) are more comprehensive tidal calculation packages, incorporating these external forcings, and other, more recent, specialist earth tide packages are available.

It may well be that more critical analysis will show that either or both of the two cases presented here are statistical chimeras. But, if not, their causal mechanisms warrant investigation, so I present this as a challenge for others to pursue.

Acknowledgments

The Bárðarbunga earthquake data were taken from the website of the Icelandic Volcano Observatory of the Icelandic Meteorological Office, and the VT string data were kindly provided by the Montserrat Volcano Observatory; I salute the hard work of all these colleagues and applaud their generosity in sharing their data. This said, the views expressed, and any inaccuracies, are mine. The author thanks an anonymous reviewer and editors Chuck Connor and Laura Connor for their constructive comments. Partial support was provided by the UK Government Foreign & Commonwealth Office Scientific Advisory Committee on Montserrat Volcanic Activity, by an ERC Advanced Research Grant (VOLDIES) to Prof RSJ Sparks FRS, and by the CREDIBLE consortium funded by the UK Natural Environment Research Council (Grant NE/J017299/1).

Additional Files

An additional file is available for download: `data_and_Schuster_tests.xlsx`

This Excel workbook contains the timings of Bárðarbunga magnitude 4+ earthquakes, the Soufrière Hills Volcano VT strings, corresponding daily vertical earth tide peaks, and the calculations of the Schuster test R parameter for these two datasets.

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